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VENTILATION OF A CITY IN A DISTINCT RELIEF DURING LOW EXCHANGE WEATHER CONDITIONS

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Abstract: The effectiveness of different urban ventilation systems during clear and calm nights in large cities in a distinct relief is investigated taking the city of Cologne (Germany) as an example. Based upon a study on summer nights in 1995 (Kuttler et al., 1997), this study deals with nights of a one year period with a more detailed time series analysis. The three wind systems found affect the urban ventilation at different night times and in different areas. The country breeze which occurs in the first half of the night can not ventilate the city centre, but only the transition zone between open areas and the built-up area, as a result of unfavourable location of ventilation paths. The down-slope winds which are observed during the whole of the night only reach the suburbs. Only the regional down-valley wind which occurs during the second half of the night ensures effective ventilation in the city centre.

Key words: Urban ventilation, Clear and calm nights, Country breeze, Down-valley wind, Down-slope wind

1 INTRODUCTION

Compared with the surrounding countryside of a city, the boundary layer of the urban atmosphere in large cities is characterised by higher pollutant concentrations and higher temperatures. If ventilation is also inadequate, these conditions could lead to critical bioclimatic situations (Mayer, 1993). In urban areas insufficient ventilation usually occurs during meteorological high pressure situations with low vertical air exchange and calm horizontal winds, especially during the night when a ground inversion occurs. Under these conditions, an urban heat island can be formed in the city (Kuttler, 1988, Oke, 1995), resulting in thermal stress for inhabitants, especially in summer nights.

During clear and calm nights, it is theoretically possible for two different ground level wind systems to ensure effective ventilation of a city despite the disconnection of the ground level wind field from the overall wind regime due to the ground inversion. As a result, critical air hygienic and thermal situations may be improved. Due to differences in air temperature and pressure between a city and its countryside which are caused by the urban heat island, the transport of colder air from the countryside into the city mainly takes place thermally as country breeze (Barlag and Kuttler, 1991). In distinct relief cold air transport takes place by gravitational cold air flow (Hauf and Witte, 1985, Freytag, 1988). In cities located in distinct relief, additional gravitational cold air flow can strengthen, overlap or replace thermally induced winds as a function of the quantity and speed of the transported air (Kuttler et al., 1996). The effectiveness of the two cold air transport mechanisms on urban ventilation depends on the size of cold air production areas in the surrounding countryside, their distance from the city centre and on the existence of smooth ventilation lanes (Kuttler, 1996, Mayer, 1996). The effectiveness of the country breeze is also a function of the intensity of the urban heat island (Oke, 1995).

In Cologne, a German city with about 1 million inhabitants located in the distinct relief of the northern Rhine Valley, Kuttler et al. (1997) found both the county breeze and gravitational cold air flow to be active in different ways during 25 clear and clam nights of the very hot summer months July and August 1995. The city ventilation of Cologne was controlled by three different ventilation systems:

1. Thermally induced country breeze with the transport of cold air from suburban cool open areas into ventilation areas, but not into the city centre,
2. Local down-slope winds with cold air flowing from the foot of the eastern bordering slope into the suburbs,
3. Regional down-valley wind ventilating the whole built-up area including the city.

In this study, data is available now for a one year measuring period, containing almost twice as much clear and calm nights from all seasons, allowing to prove if the "best case study" of the summer 1995 is a regular phenomenon in the ventilation of the Cologne city during clear and calm nights.

2 SITE DESCRIPTION

A detailed regional site description is given in Kuttler et al. (1997). Figure 1 shows an regional view of the Cologne Bay, a flat inclined geomorphological delta in West Germany, widening to the north-west and falling off at the Lower Rhine Lowlands. The investigation area (φ = 50°52'N, λ = 7°05'E) is situated east of the River Rhine.

The decrease in altitude of the investigation area is less than 2 m/km perpendicular to the River Rhine. The investigation area can be characterised as a wedge-shaped, predominantly green area entering the developed area of Cologne from the east (Figure 2). The wooded foot of the slope directly to the east of the investigation area at the so-called Königsforst (see Figure 1) has an inclination of 17 m/km.

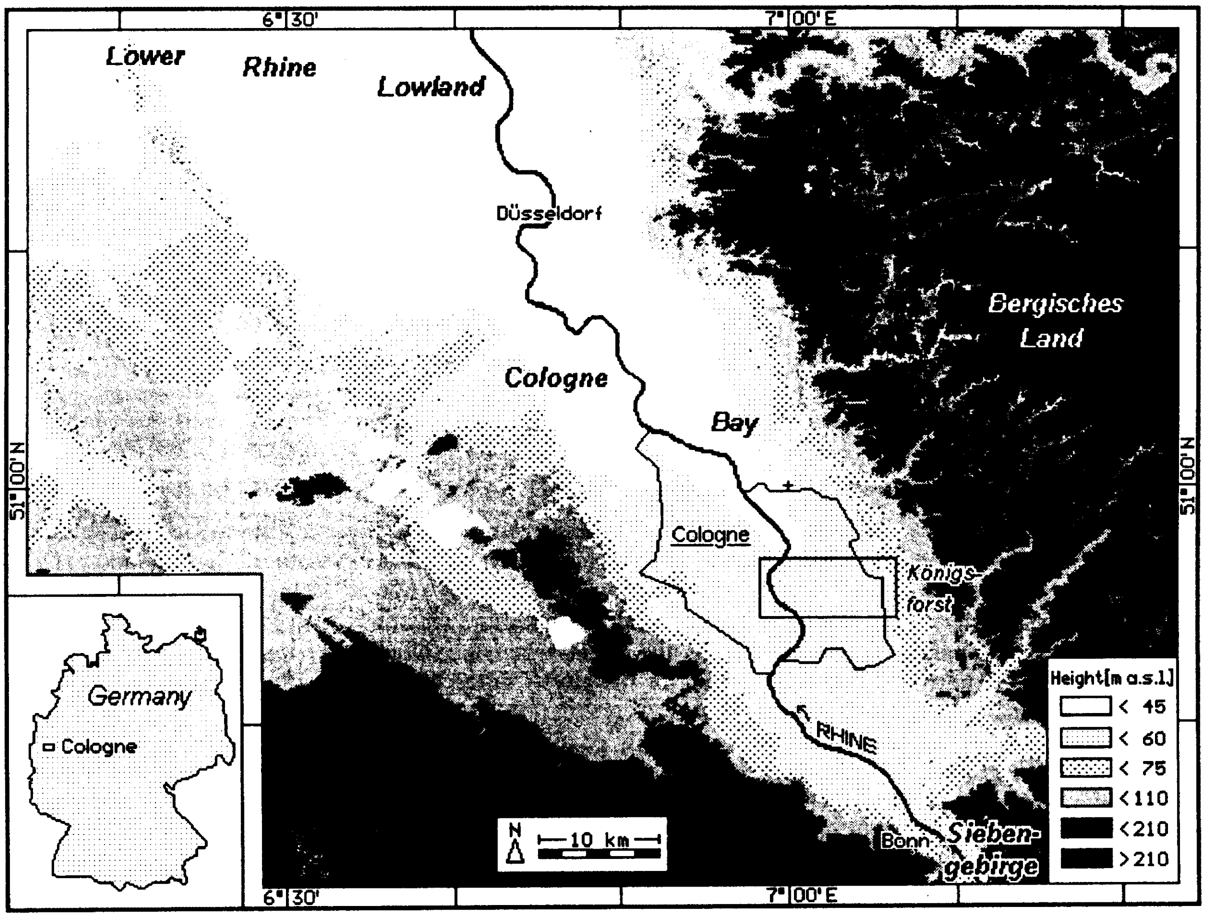

Figure 1 Regional view of the investigation area. River and city border sketched in. Rectangle: Map of the investigation area (see Figure 2).

3 METHODS

Stationary and mobile measurements were the basics of this investigation. For technical and methodical details of this investigation compare to Kuttler et al. (1997).

The stationary measuring network consisted of eight ground stations and a rooftop station. For location and characteristics see Figure 2 and Table 1. Air temperature, air humidity and net radiation were recorded at 2 m a.g.l. as well as wind velocity and wind direction at 4 m a.g.l.

Each station recorded around 6000 three-minute mean values for 44 clear and calm nights during low exchange weather conditions between July 1995 and July 1996. 76% of the selected nights were under the influence of the European meteorological high pressure situation types NEa, BM and HNFa. Of the 44 clear and calm nights, 31 were in June, July and August, 5 in April, 2 in each of September, November and December and 1 in each of March and May.

Cold air production areas were defined as vegetation areas such as forests, fallow land and unsealed open surfaces. Open areas which appeared suitable for effective ventilation were determined by mapping the surface roughness of the heterogeneously structured investigation area as z_0. Following Matzarakis and Mayer (1992), $z_0 < 0.5$ m and a length to width ratio of 1000 : 50 m were chosen as sufficiently low roughness and sufficient area extension for undisturbed cold air transport.

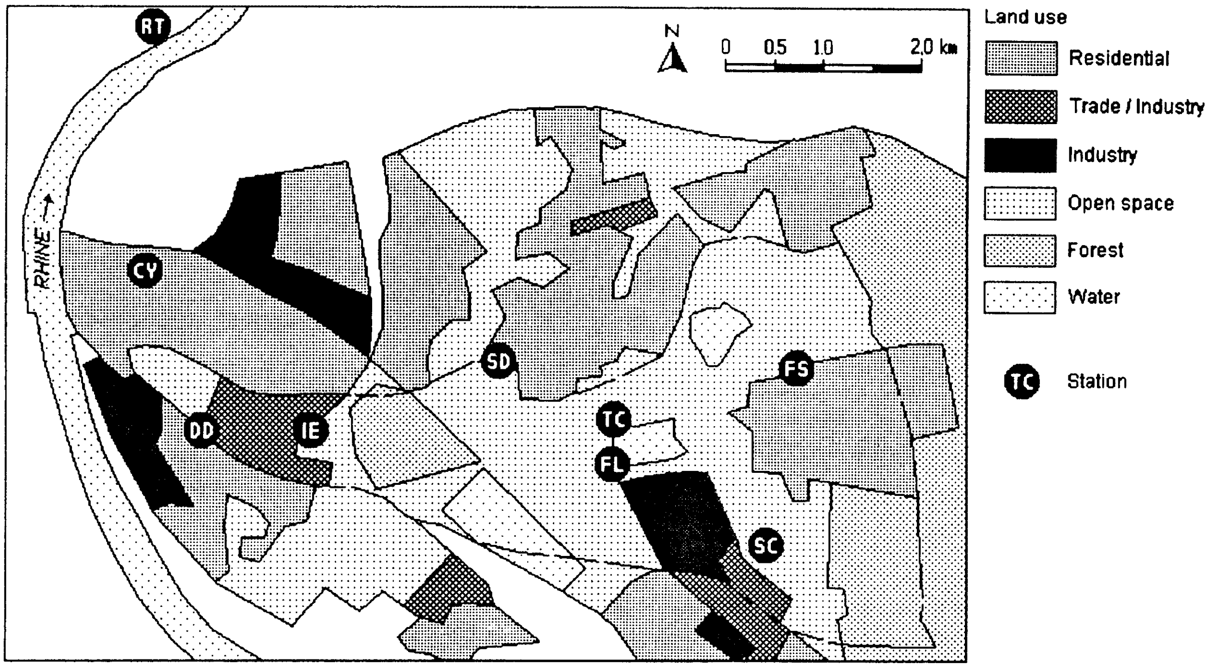

Figure 2 Simplified map of the investigation area in Cologne including land utilization and stations (white areas are outside the investigation area).

Table 1 Characteristics of the measuring stations in the investigation area in Cologne.

Station	**Altitude (m a.s.l.)**	**Measuring quantities *)**	**Characteristics of the surroundings**
FS (Foot of the slope)	50	ϑ_a, U, u, WD	Agricultural land use, light development
SC (Surrounding countryside)	50	ϑ_a, U, u, WD	Agricultural land use, industrial estate
TC (Transition from countryside to city)	54	ϑ_a, U, u, WD	Situated on banks of earth, grass areas
FL (Fallow land)	50	ϑ_a, U, u, WD	Open fallow land, flooded quarries, industrial estates
SD (Development in the surroundings)	50	ϑ_a, U, u, WD	farmland, wood and light development
IE (Industrial estate)	45	ϑ_a, U, u, WD, Q	Industrial estate
DD (Dense development)	45	ϑ_a, U, u, WD	Cemetery, garden allotments, multi-storey buildings
CY (City)	43	ϑ_a, U, u, WD	gravel areas, railway embankment, multi-storey buildings
RT (Rooftop)	179 (137 m a.g.l.)	u, WD	Highest point, no surrounding high rise buildings

*) ϑ_a = air temperature [°C] in 2 m a.g.l., U = relative air humidity [%] in 2 m a.g.l., u = wind velocity [m/s] in 4 m a.g.l., WD = wind direction [Degree] in 4 m a.g.l., Q = net radiation [W/m^2] in 1.7 m a.g.l., a.s.l. = above sea level, a.g.l. = above ground level.

Tracer gas sulfur-hexafluoride (SF_6) was released during a suitable night in 1.5 m above ground level to determine the depth of penetration of cold air from the transition point (station IE) between the ventilation areas and the densely built-up into the city centre. The SF_6-distribution was analysed simultaneously at various points on the terrain by a mobile gas chromatograph.

To determine the meteorological elements in a vertical profile during cold air drainage an electronic tethersonde was set up over individual nights up to a height of 200 m a.g.l.

4 RESULTS

4.1 WIND FIELD OVERVIEW

In order to identify the three wind systems postulated above, first the wind field of the 44 clear and calm nights was analysed for all hours of the nights. The distribution of wind directions is indicated in Figure 3. Wind speed statistics are listed in Table 2.

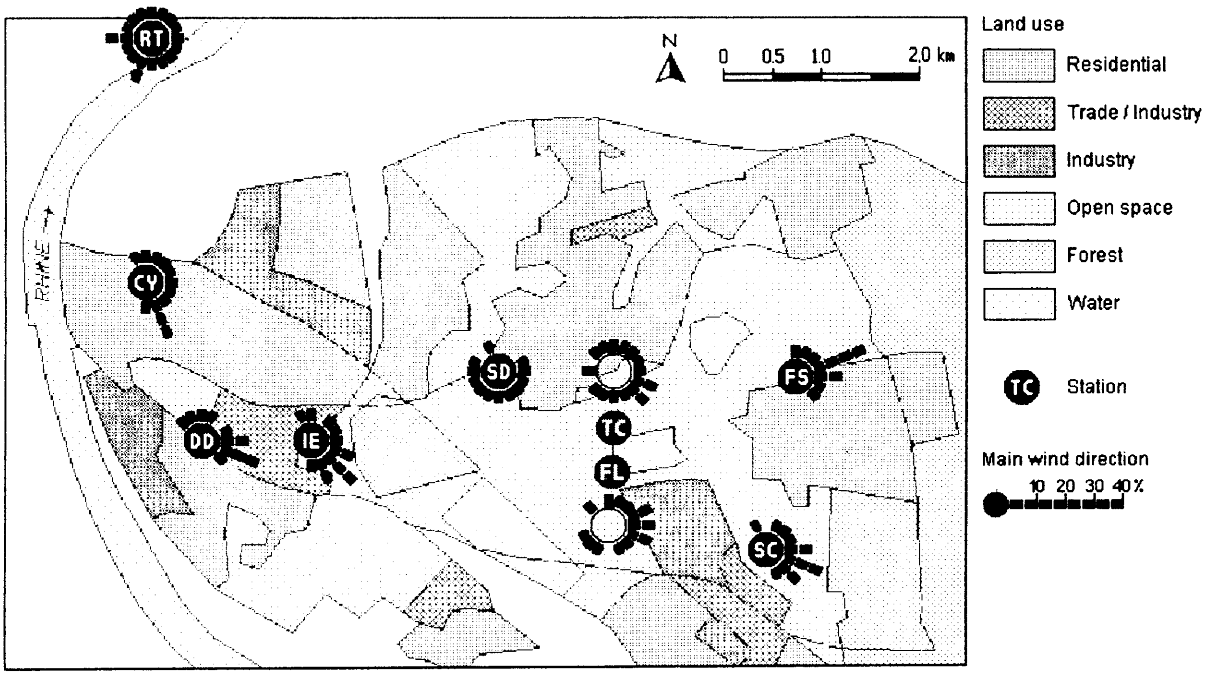

Figure 3 Main wind directions at the Cologne measuring stations for 44 clear and calm nights between July 1995 and July 1996. Data: three-minute mean values.

At all the ground stations, the wind speed was less than 1.3 m/s, with calm shares between 5% and 58% caused by station sites properties (see below). At all the stations, apart from stations FS and SC located at the foot of the slope, a southerly to south-easterly air flow was observed. This indicates air transport from the surrounding area to the inner city. The north-easterly direction detected at station FS at the foot of the slope indicates a down-slope wind flowing into the investigation area. The wind direction measured at the rooftop station RT was south-westerly to westerly, showing that the ground-level wind system was possibly disconnected from the overall wind regime.

Although these observations already give indications of a ground level air flow in the direction of the city centre, it is not possible to make a statement about the ventilation of the inner city on the basis of the ground level wind field shown in Figure 3. There are three reasons why this is the case:

1. The night wind roses of the individual ground stations do not give any indication of the time of onset of the south-easterly air flow in the direction of the city centre. The considerable variations in wind direction observed in some cases show that south-easterly winds did not persist for the whole of the night.

2. It is not possible to state whether winds in the direction of the city centre occurred at the same time at all stations. Effective ventilation would only be plausible in the case of a simultaneous wind.

3. Even if at all ground stations a flow in the direction of the city centre occurs simultaneously, it would still not be possible to determine whether the wind observed constituted one wind system or several smaller systems. As this is a densely built-up area, effective ventilation of the inner city would only be probable with a closed wind system covering all the stations.

Table 2 Distribution of temperature and wind velocity at the measuring stations in Cologne for 44 clear and calm nights between July 1995 and July 1996. Data: three-minute mean values.

Quantity *)		FS	SC	TC	FL	SD	IE	DD	CY	RT	Average
$\overline{\vartheta_a}$	[°C]	8.0	8.7	10.2	9.8	9.0	9.9	9.8	11.9	-	9.7
s_{ϑ_a}	[K]	9.9	9.7	9.7	9.7	11.5	10.0	10.0	9.8	-	9.8
$\vartheta_{a\,max._{abs.}}$	[°C]	26.5	26.1	26.9	26.5	26.9	27.4	27.4	28.2	-	26.9
$\vartheta_{a\,min._{abs.}}$	[°C]	-14.2	-13.4	-11.4	-12.2	-13.8	-13.0	-12.2	-9.5	-	-12.4
$\bar{u}$	[m/s]	1.0	1.3	1.3	1.1	0.4	0.7	0.5	1.1	2.2	1.1
s_u	[m/s]	0.5	0.6	0.6	0.6	0.5	0.6	0.5	0.5	1.0	0.6
Calms	[%]	10.7	6.7	4.9	10.8	57.6	38.4	51.2	11.3	0.4	21.3

*) $\overline{\vartheta_a}$ = average air temperature, s_{ϑ_a} = standard deviation of air temperature, $\vartheta_{a\,max._{abs.}}$ = absolute measured maximum air temperature, $\vartheta_{a\,min._{abs.}}$ = absolute measured minimum air temperature, $\bar{u}$ = average wind velocity, s_u = standard deviation of wind velocity.

In addition, in view of the positions of the open areas in relation to the inner city and the eastern edge of Cologne Bay (cf. Figure 1), a closed, simultaneous air flow from all the stations during clear and calm nights can be explained theoretically by two different wind systems which are difficult to distinguish due to the same orientation of their wind direction: 1. a country breeze with a south-easterly component induced by the Cologne urban heat island and 2. a regional south-easterly down-valley wind which could be reinforced by easterly down-slope winds, especially in the investigation area.

A regional south-easterly down-valley wind caused by the large-scale relief has already been described for the eastern part of Cologne Bay by other authors (Band, 1961, Ebel, 1962 or Grober, 1973). However, detailed investigations of the influence of this regional wind system or a country breeze on the ventilation of the inner city area of Cologne have not yet been made. Information on the times when and the areas where theses wind systems are effective would be of considerable practical importance for urban planning in the city of Cologne.

In this paper the three possible wind systems country breeze, down-slope wind and regional down-valley wind are analysed and assessed with regard to their importance for the ventilation of the inner city.

4.2 COUNTRY BREEZE

The determination of the prerequisites for a county breeze is necessary first to distinguish it from the other two wind mechanisms described in the introduction chapter above. The most important prerequisite is the urban heat island, complemented by cold air production areas in the nearby countryside and ventilation paths, reaching from the surrounding cold air production areas into the city.

The urban heat island was determined with the temperatures measured at the eight ground stations (Table 2). These data reflect the decrease of temperature between the city centre and the surroundings during the 44 clear and calm nights. The intensity of the urban heat island was defined as the horizontal temperature difference $\Delta\vartheta_{u\text{-}r}$ between the warmest city station and the coldest station in the countryside. Theses are the city Station CY ($\overline{\vartheta_a}$ = 11.9°C) and Station FS ($\overline{\vartheta_a}$ = 8.0°C) at the foot of the slope in the surroundings, leading to $\Delta\vartheta_{u\text{-}r}$ = 3.9 K in average and to maximum values of 5.7 K during individual nights. A largely uniform temperature level of $\overline{\vartheta_a} \approx$ 9.7°C exists along the open spaces between the transition of the densely built-up areas and outer open spaces. Mobile temperature measurements confirmed that this applies over a large area.

As shown in Figure 4, the urban heat island starts to build up at sunset, reaching its maximum intensity between 22:00 CET (Central European Time) and dawn, at about 05:00 CET. The formation of an urban heat island can therefore be observed in the city of Cologne during clear and calm nights.

Figure 5 shows the cold air production areas in the surroundings which are necessary for the formation of country breezes. They were determined by mapping as green and wooded areas. These 14 km^2 cold air production areas stretch from the foot of the slope of the Bergisches Land into the built-up area of Cologne, however, never reaching the city centre.

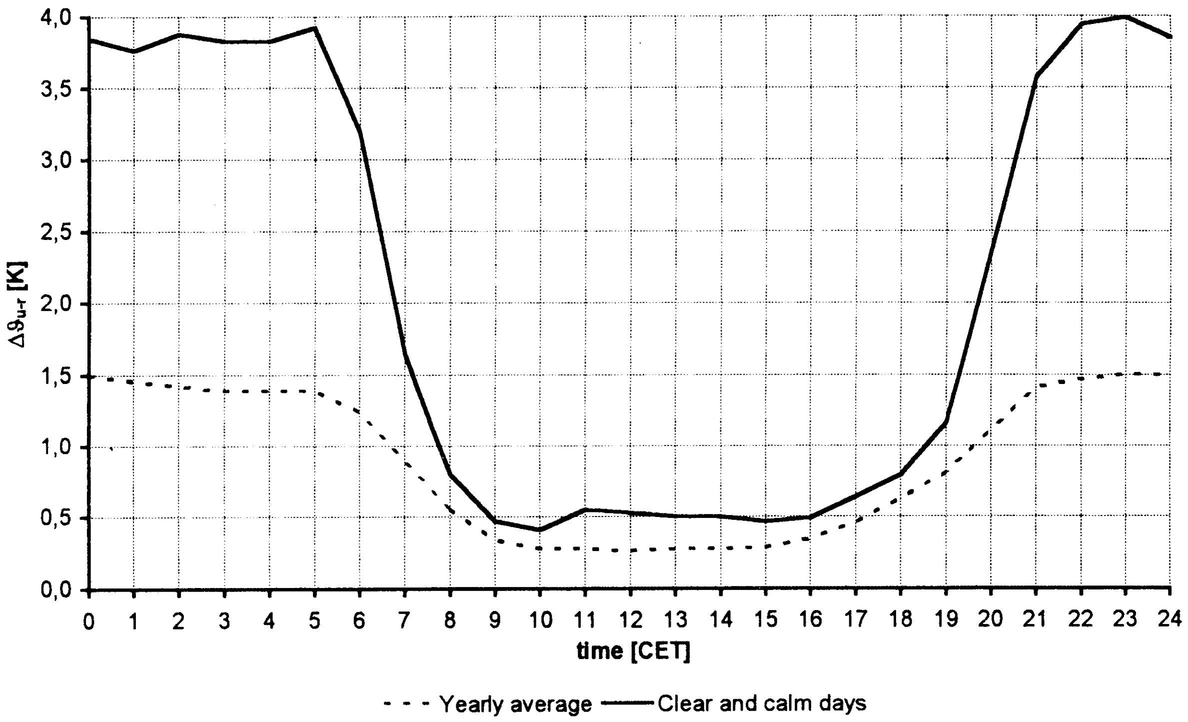

Figure 4 Average daily course of the urban heat island intensity $\Delta\vartheta_{u-r}$ [K] in Cologne over the measurement period July 1995 to July 1996 and for 44 clear and calm days in the same period. Data: 1-hour mean values.

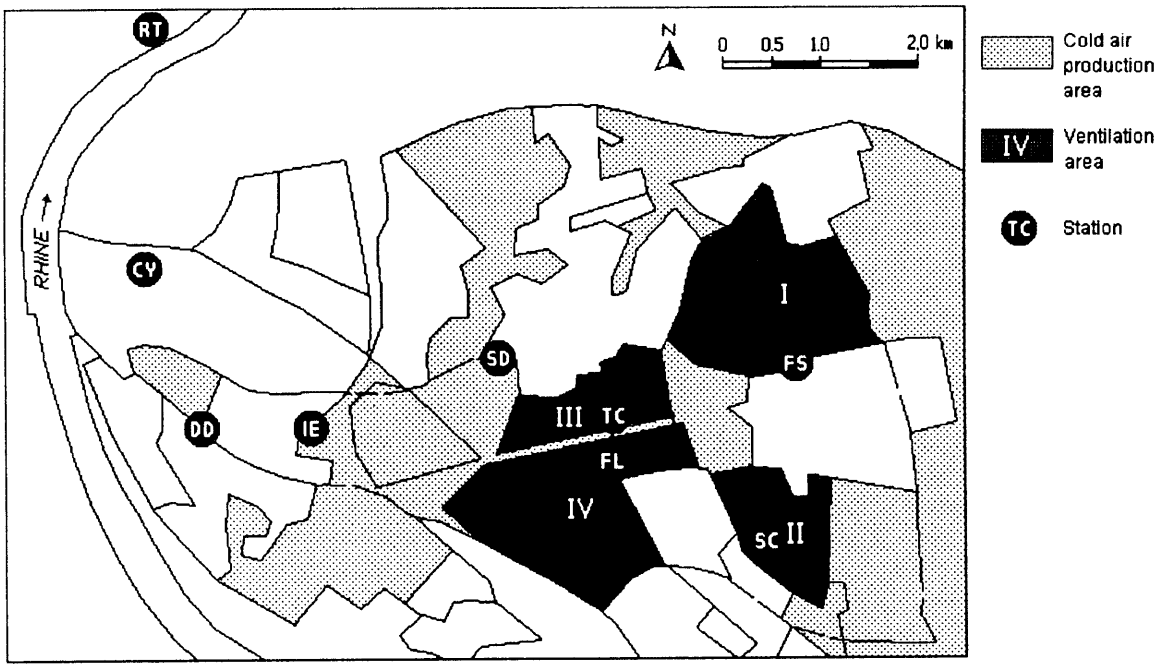

Figure 5 Cold air production areas and ventilation areas in the investigation area in Cologne.

As also shown in Figure 5, four ventilation areas, together totalling 12 km^2, are found in the investigation area. These areas (No. I to IV) are situated within the cold air production areas but are separated by obstacles which can not be shown in detail in the figure. These obstacles are industrial estates, wooded areas and motorway embankments with an average height $h > 10$ m which could obstruct the flow of cold air (King, 1973). As a result, there are no closed continuous ventilation paths from the surroundings into the city centre, but rather subdivided areas. Moreover, since the ventilation areas do not completely cover the cold air production areas and are relatively far from the city centre, it is questionable whether cold air formed by the cold air production areas can be directed into the city centre over these ventilation areas.

In order to determine the country breeze, the time series of wind directions of the ground stations were analysed as a function of the time of the day. The relative frequencies of the wind directions at the stations at certain times in the night are shown in Figure 6 in the form of isopleths.

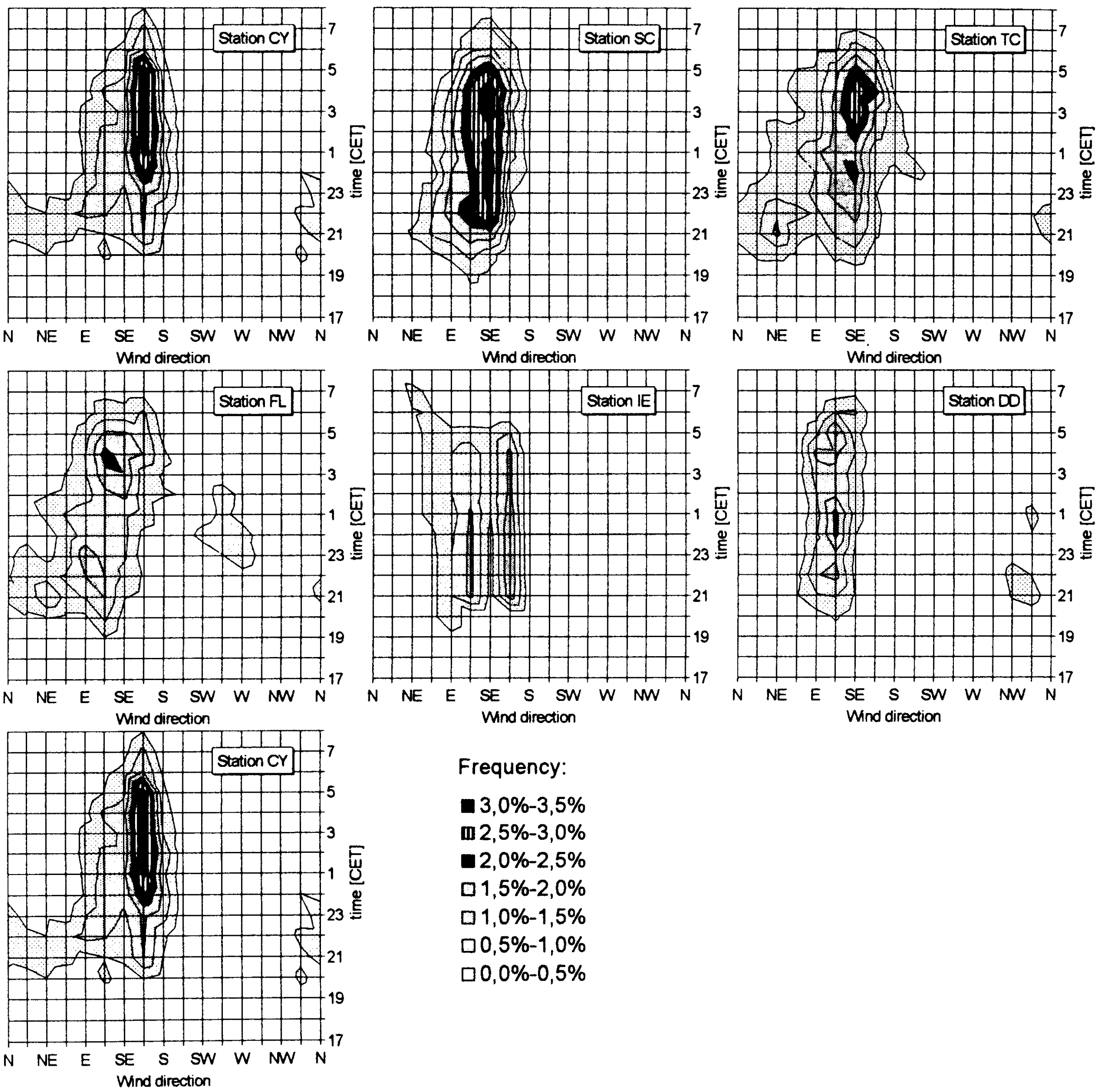

Figure 6 Wind direction isopleths for different night times at the ground stations in the Cologne investigation area for 44 clear and calm nights between July 1995 to July 1996. Data: three-minute mean values.

Taking into consideration the positions of the stations and the wind speed statistics listed in Table 2, in the first half of the night between 20:00 CET and about 02:00 CET severe fluctuations in wind direction are apparent in the entire eastern sector, especially at stations TC and FL in the surroundings, transitional station IE and station CY in the inner city. According to Figure 4, the urban heat island already reached its maximum intensity at 22:00 CET during this time period. Although the prerequisites for a thermal wind at ground level were given for about four hours in the first half of the nights, there was nevertheless no air flow from the stations in the direction of the inner city. The wind field of station DD is determined by the channelling effect of straight rows of buildings which cannot be shown on the map in Figure 2.

After about 02:00 CET, a concentration of wind direction in narrow sectors is apparent at almost all ground stations. In view of the position of the stations, this concentration indicates a flow of cold air towards the city centre which could be interpreted as a country breeze occurring after midnight. However, on the basis of isopleths of wind direction frequency as a function of urban heat island intensity $\Delta\vartheta_{u-r}$ (Figure 7), it can be shown that the concentrated winds at ground level do not represent a country breeze.

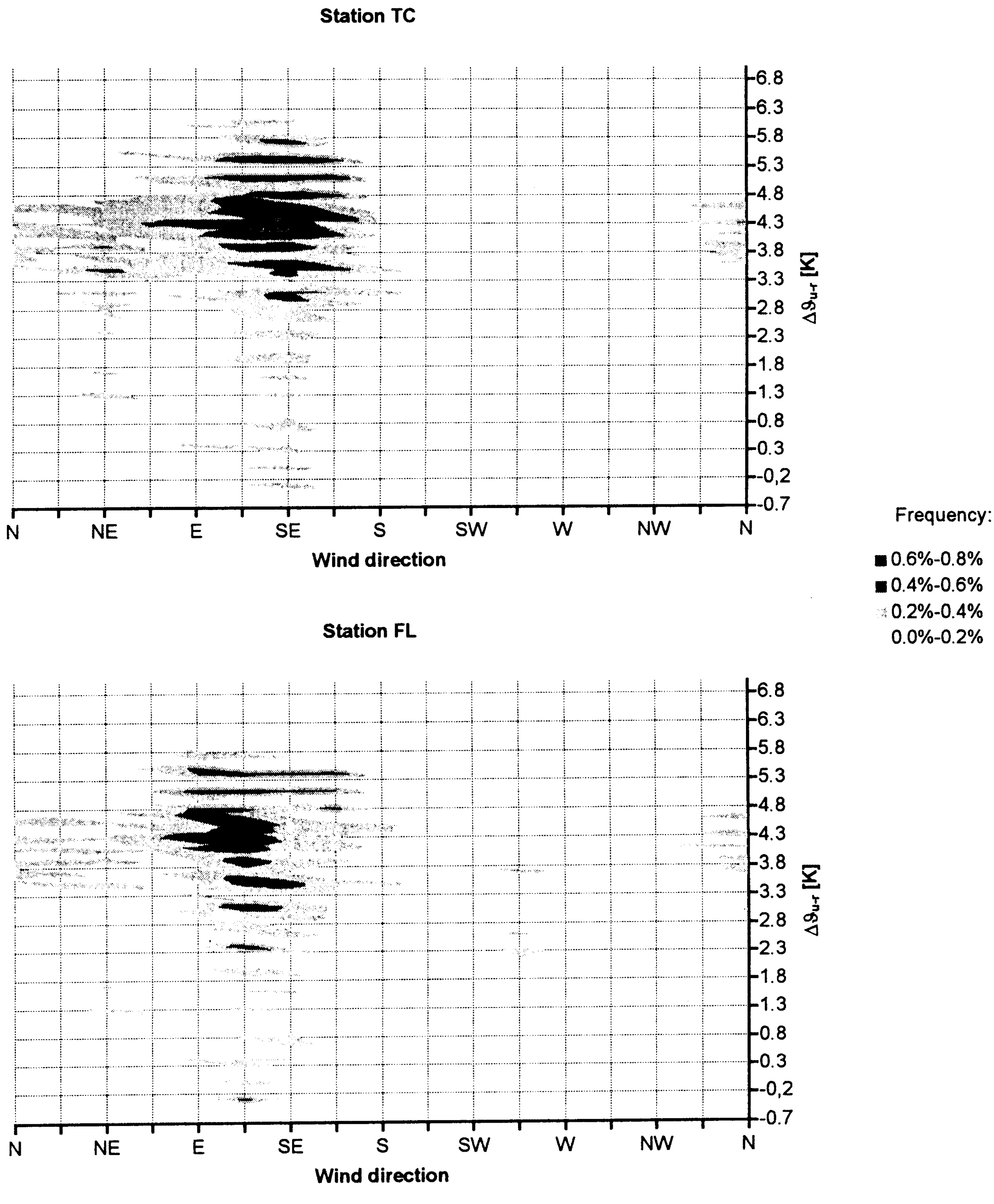

Figure 7 Wind direction isopleths as a function of the urban heat island $\Delta\vartheta_{u-r}$ [K] at stations TC and FL in the Cologne investigation area for 44 clear and calm nights between July 1995 to July 1996. Data: three-minute mean values.

As an example, stations TC and FL, located nearest to the city centre in ventilation areas III and IV were taken. In view of the orientation of open spaces, these would be the stations where a cold air transport from the surroundings into the city would be expected. Within a range of ± 1.5 K around the average maximum heat island intensity of $\Delta\vartheta_{u-r}$ = 3.9 K, no predominant wind direction in the east sector could be found at either of the stations. This means that there was no thermally induced cold air transport in the direction of the inner city from these stations on the 44 clear and calm nights investigated. Although all the thermal prerequisites are met, the country breeze therefore does not reach the inner city. The reason is the severe fragmentation of open areas and the considerable distance between these areas and the city centre. The industrial area to the south-east of station FL and a motorway intersection positioned on an embankment >10 m a.g.l., oriented in a north-south direction to the east of stations TC and FL, prevent cold air flowing from ventilation areas I and II into ventilation areas III and IV. In turn, the cold air production of ventilation areas III and IV is too low for the formed cold air to be carried to the inner city via the woods to the east of station IE by a country breeze.

4.3 DOWN-SLOPE WIND

Down-slope winds from the neighbouring slopes in the east of the investigation area are observed over the whole night at the slope bottom stations FS and SC, as shown in Figure 6. At these stations there is a large share of winds from ENE and ESE, respectively, with relatively few calms (9% on average). These continuous flows must be interpreted as independent down-slope winds from the Königsforst. This assumption is especially confirmed by the location of station FS which is shielded against south-easterly airflow by the housing estate to the south, effecting the strong north-easterly flow perpendicular to the slope. With regard to the separation of the ventilation areas and the fact that there is no air flow via ventilation areas III and IV to the city centre, these down-slope winds play no significant role in the ventilation of the city centre. It can be supposed, therefore, that the prevailing east to south-easterly wind direction in the whole investigation area is not controlled by a country breeze and local down-slope winds.

4.4 REGIONAL DOWN-VALLEY WIND

On basis of Figures 6 and 7, it was shown that the steady-direction air flows at the ground stations after 02:00 CET are not caused by country breeze. Therefore this constant air flow must be caused by a larger-state wind system. The wind field in the investigation area in Cologne is determined by regional cold air flow from the southern part of the Cologne Bay, where cold air has been formed and accumulated since the beginning of the night under corresponding meteorological conditions in suitable open spaces. Furthermore, cold air from the relatively narrow and deeply carved Rhine valley south of the Cologne Bay flows into the opening Cologne Bay during a clear and calm night (Klaus, 1988) as "Siebengebirgswind" (Luft, 1938). During the advancing night both cold air masses begin to flow down-valley as Rhine Valley Wind in a north-westerly direction following the lightly sloping terraces of the Rhine Valley. Ebel (1962) was able to prove the regional character of this south-easterly down-valley wind for the northern Rhine Valley by considering the wind field in Düsseldorf separately for the two halves of clear and calm nights. He found that the wind turned from NE in the first half of the night to SE after midnight. The advected regional cold air is superimposed and mixed on the local cold air flow in the Cologne investigation area and directed into the city centre.

This hypothesis is confirmed by the wind directions after 02:00 CET shown in Figure 6. In particular at stations SC, TC, FL, IE, and CY, it can be proved that the Rhine Valley Wind flows in the direction of the city. The Rhine Valley Wind carries along the cold air which was formed in the open spaces of the investigation area in the early night. It is important to study its spatial effectiveness with regard to both penetration into the city and vertical extension.

For this purpose, an investigation of cold air distribution with SF_6-tracer gas combined with vertical soundings was carried out in the clear and calm night from 9th to 10th August 1995 at Station IE at the transition between the surroundings and the densely built-up area. For details of this investigation compare to Kuttler et al. (1997). As shown in Figure 8, the main wind directions at selected stations near to the river reflect the air stream parallel to the River Rhine for the SF_6-measuring period between 01:49 and 04:47 CET. The ground level distribution of SF_6-tracer gas concentration shows that cold air was transported across an area of about 7 km² from the surrounding area into the city up to the River Rhine in spite of the densely built-up area. It can therefore be assumed that during the second half of the night the Rhine Valley Wind carries along both the air from the southern part of the Cologne Bay together with the air formed in the local cold air production areas through the investigation area into the densely built-up area.

For the Rhine Valley Wind a vertical extension of around 100 m was determined by several vertical soundings carried out at station IE in several clear an clam nights. In Figure 9, there are shown examples of vertical profiles taken in the early morning (05:00 CET) of the SF_6-investigation night on 10th August 1995. The absence of the relatively indifferent to unstable ground level stratification typical of industrial locations confirms that the effects of the Rhine Valley Wind penetrate to ground level. As a result, the Rhine Valley Wind carries along the cold air from the cold air production areas in the direction of the city. In the lowest

20 m within this inversion a distinct, calm, south-easterly wind stream was identified caused by the local surface roughness. Above the inversion an increase of 5.5 to 7.0 m/s in wind velocity was identified between 100 and 160 m above ground level, possibly pointing to the presence of a low level jet. Roth (1987) was able to prove a frequent appearance of low level jets in the North-West German Lowlands.

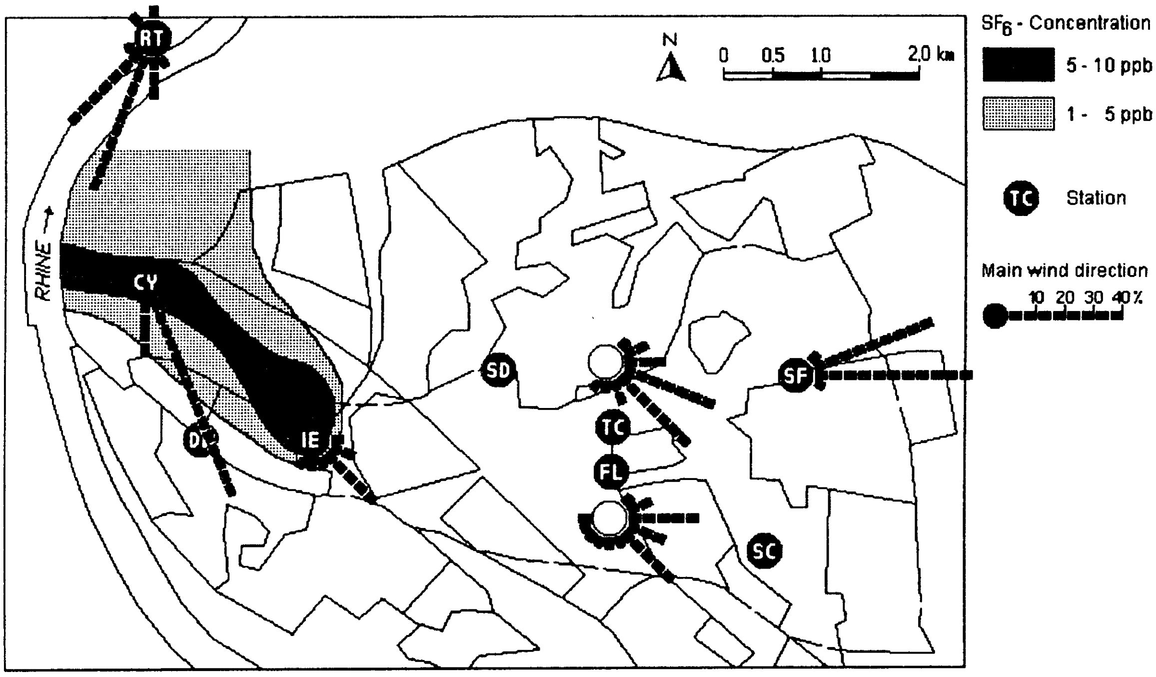

Figure 8 SF_6-distribution and main wind directions between 01:49 and 04:47 CET during the clear and calm summer night from 09th to 10th August 1995 at selected stations in Cologne. Data: three-minute mean values.

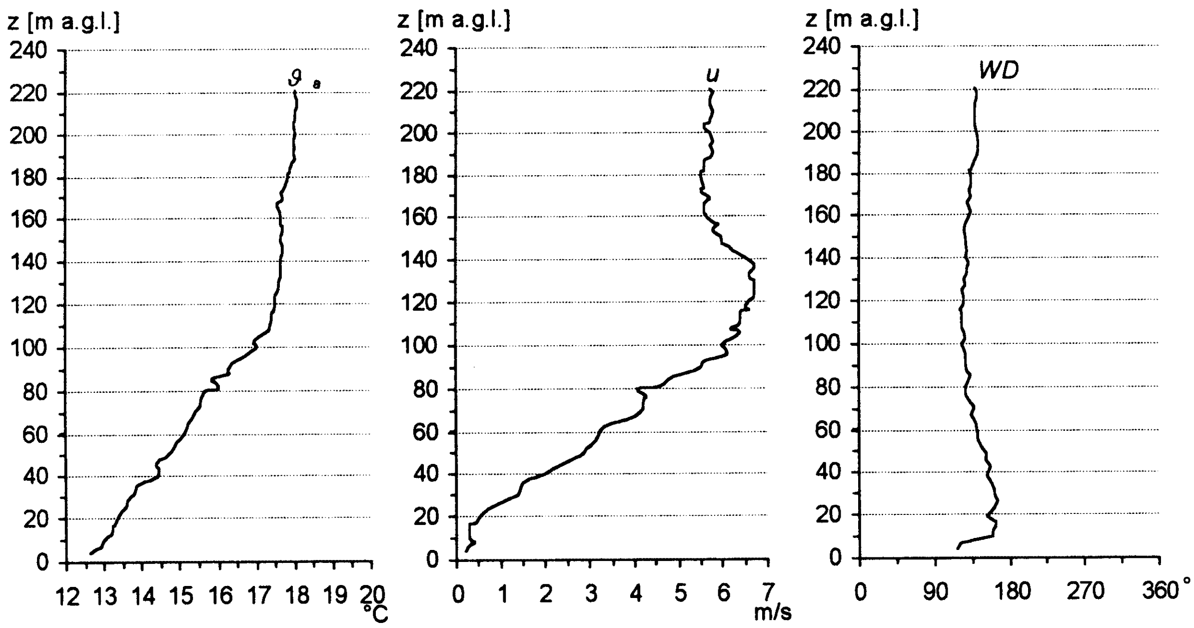

Figure 9 Vertical profiles of air temperature ϑ_a, [°C], wind velocity u [m/s] and wind direction WD [Degree] on the outskirts of the built-up area (Station IE) in Cologne in the morning of 10th August 1995 at 05:00 CET. (z = height above ground level.) Data: 78 10-second interval measurements.

5 CONCLUSION

In accordance with the results found for the summer nights in 1995 (Kuttler et al., 1997), the ventilation of the Cologne city during clear an calm nights is independent of seasonal effects. Three different wind systems influenced by the distinct relief of the Cologne Bay can occur during clear and calm nights in the part of Cologne to the east of the River Rhine. There are significant differences between the spatial structure of these systems and the times when they are active (Figure 10 and Table 3).

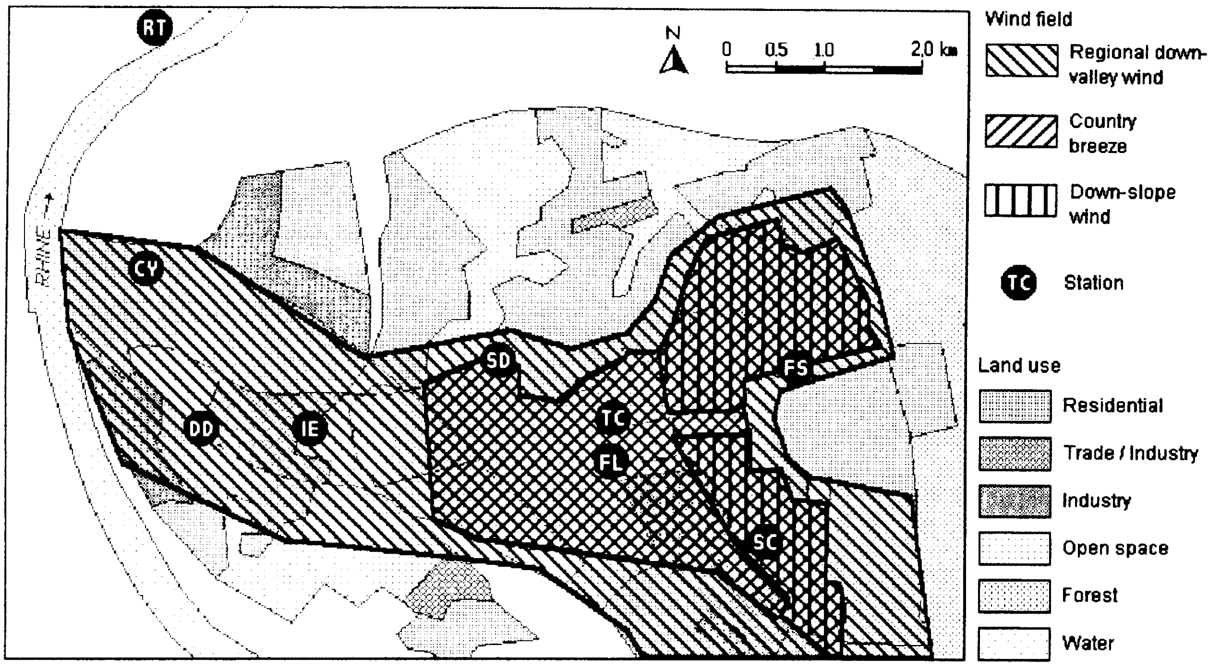

Figure 10 Spatial effects of different wind systems inside the investigation area in Cologne during 44 clear and calm nights calm nights between July 1995 and July 1996.

Table 3 Spatial and time effects of different wind systems in the investigation area in Cologne during 44 clear and calm nights between July 1995 and July 1996.

Characteristics	Regional down-valley wind (Rhine Valley Wind)	Country breeze	Down-slope wind
Occurrence time:	from 02:00 CET	whole night	whole night
Area affected:	whole investigation area including densely built-up parts	all open areas	open areas along foot of slope
Ventilation of built-up areas:	all built-up areas including city centre	at transition between densely built-up parts and surroundings	suburbs

In the first half of clear an calm nights, prior to the onset of the Rhine Valley Wind from about 02:00 CET, ventilation of the city centre is inadequate. The country breeze and the down-slope wind are only of secondary importance for the ventilation of the city centre. In open areas outside the core of the city centre there are some traces of country breeze in the form of microscale circulations. Although these are mainly directed toward the city centre, they do not reach it as a result of the considerable distance from the city centre and the subdivisions of the open areas. However, these microscale circulations are significant for the ventilation of the outlying built-up areas.

The down-slope winds which can be observed during the whole of the night only ventilate open areas and their neighbouring built-up areas at the foot of the slopes on the extreme edge of the city and are therefore also of no significance for ventilation in the city centre.

In the second half of clear an calm nights, the Rhine Valley Wind superimposes itself on the local wind systems after 02:00 CET. The Rhine Valley Wind flows across the investigation area, carrying along the cold air from the cold air production areas and ensuring effective ventilation of the city centre.

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